A METHOD FOR CONTROLLING A SYSTEM FORMED FROM INTERDEPENDENT UNITS

FIELD OF THE INVENTION

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The present invention relates generally to systems formed from a plurality of interdependent units and more particularly to methods to control such systems to achieve an outcome, and control systems that implement that
10 control methodology. The invention has been described, but is not exclusively directed to, a control methodology for a mechanical device such as a robot.

BACKGROUND OF THE INVENTION

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Robots, and in particular, a sub-class of robots which are termed "manipulators" in the art, have primarily been limited to hard automation applications (such as welding metal plates together on an assembly line) due to
20 their task specific design. Traditional centralised control models rely on pre-programmed knowledge regarding the surrounding environment and the specific task requirements.

Due to the need for pre-programmed knowledge
25 regarding the surrounding environment, robots engaged in complex movements are generally incapable of adapting to changing circumstances or of successfully completing tasks when faced with unfamiliar situations.

For this reason, robots have been limited to '
30 applications where the task to be performed requires repetition, precise movement and high speed. However, as the demand for automation has increased, there has been an increasing need to provide robots with increasingly

sophisticated control mechanisms that allow the robotic device to perform successfully in dynamic and unpredictable situations.

Furthermore, robots which have many interdependent
5 parts generally utilise complex algorithms in order to determine appropriate movement from one position to another. Complex algorithms are necessary because, in a robot with multiple interdependent units (i.e. a plurality of units that are constrained by each other in some
10 manner, such as being physically linked or controlled) and multiple degrees of freedom, there are multiple possible solutions in moving from one point to another. That is, attempting to solve equations which determine how each unit should move, to move the robot to the desired
15 position, result in multiple redundant solutions.

Therefore, complex algorithms must be used to determine which of the multiple possible solutions must be utilised. This usually involves the application of artificial boundary conditions to limit the degrees of
20 freedom of the robot.

SUMMARY OF THE INVENTION

In a first aspect, the present invention provides a
25 method for controlling a system formed from a plurality of interdependent units to achieve an outcome, comprising the steps of establishing a desired outcome for the system, and establishing a desired action for each unit responsive to the outcome but independently of the desired action of
30 the other units.

In a second aspect, the present invention provides a method for controlling a system formed from a plurality of interdependent units to achieve an outcome, comprising the

steps of establishing a desired outcome for the system,
and establishing a desired action for each unit responsive
to the outcome, wherein the desired action for a said unit
is established in response to the current position of at
5   least one reference portion of the system relative to a
desired position of that reference portion.

The desired action for a said unit may involve
calculating a difference value between the current
position of a said reference portion and the desired
10   position of that reference portion, and using said
difference value to establish said desired action.

In other words, in at least an embodiment, each unit
is provided with some information regarding a desired
outcome (a "goal") and is also provided with a reference
15   position. Each unit then seeks to calculate a value which
is indicative of the desired action the unit must take if
it is to reach its goal. This may, in some embodiments,
be a difference value between a reference position and a
desired position.

20   The method may include the further steps of
establishing an operation action for each unit; and
instructing each unit to initiate its operation action.

The method may comprise the further step of iterating
the method steps to update the operation action, and the
25   rate may either be constant throughout the system, or may
vary between units of the system.

The operation action for at least some of the units
may be the desired action. In most cases, the desired
action will be the best action for the unit to take in
30   assisting the unit to work towards the desired outcome.
However, individual links may come across constraints,
such as obstacles, or the breakdown of other links.

In such a case, the method may include the further

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steps of establishing constraint factors for the system, and establishing a constrained action for at least one unit responsive to the constraint factors. The constrained action may override the desired action, or the

5   constrained action and the desired action may be compared and a compromise sought.

That is, the operation action for a unit for which a constrained action has been established is the constrained action.

10   Once the constrained action is established, only the constraint factors for a unit may be utilised in establishing the constrained action for that unit.

However, in another form, the constraint factors relating to at least one unit may be utilised in

15   establishing a said constrained action for another said unit.

The method may also be utilised to control more complex movements, such as the movement of a manipulator along a defined path, or the intersection of a manipulator

20   with a moving object. In such as case, the method may include the further step of establishing a plurality of intermediate outcomes to achieve the desired outcome.

In the case where there are a plurality of intermediate outcomes, the desired actions of the units

25   may be established in response to individual ones of the intermediate outcomes.

The method steps may be iterated so that a plurality of the desired actions for each unit is established over time, and whereby the desired actions may be established

30   responsive to a plurality of the intermediate outcomes.

In addition to being utilised for complex behaviour, the method may also be utilised for complex systems. That is, in situations where the system comprises a series of

subsystems, where each subsystem being comprised of at
least one of the plurality of interdependent units, the
method may further include the steps of establishing a
said intermediate outcome for each subsystem, whereby the
5   desired action for each unit is established responsive to
the intermediate outcome of the subsystem to which it is
associated.

That is, each subsystem functions like a
self-contained system, with the intermediate outcome as
10   their immediate goal, where the intermediate outcome is
sympathetic with the desired outcome for the system as a
whole.

It will be understood that the outcome may be
dependent on a spatial relationship of the system, and
15   moreover, the outcome may also be a predetermined spatial
relationship of the system relative to a desired location.

The outcome may also time dependent.
the desired action involves adjusting the spatial position
of that unit. In situations where there are no
20   constraining factors, the outcome may be the sole
determinant of the desired position.

The adjustment may be by way of movement of the unit
and/or expansion or contraction of that unit.

In a third aspect, the present invention provides a
25   method for controlling a plurality of interdependent
units, comprising the steps of, for each unit,
independently deriving an operation action, the operation
action being responsive to starting information.

The starting information is selected from the group
30   comprising a desired outcome, a desired action, a
constraint action and a reference position.

In a fourth aspect, the present invention provides a
system for controlling a plurality of interdependent units

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moveable to achieve an outcome, the system comprising a
controller arranged to implement a control methodology in
accordance with a first aspect of the invention.

In a fifth aspect, the present invention provides a
5   computer program arranged to, when loaded on a computing
system, perform the method in accordance with a first
aspect.

In a sixth aspect, the present invention provides a
computer readable medium incorporating a computer program
10   in accordance with a fourth aspect.

DETAILED DESCRIPTION OF THE DRAWINGS

Further features of an embodiment of the present
15   invention will now be described, by way of example only,
with reference to the following figures in which:

Figures 1a and 1b are schematic diagrams of an
individual link of a manipulator in accordance with an
embodiment of the present invention;

20   Figure 2a is a schematic diagram illustrating a
manipulator in accordance with an embodiment of the
present invention and Figure 2b is a schematic diagram
illustrating a manipulator in accordance with another
embodiment of the present invention;

25   Figures 3a to 3c are a series of graphs that describe
the simulated movement of a manipulator in accordance with
an embodiment of the present invention;

Figures 4a to 4f are a series of graphs that describe
the actuation angle for each link, as a function of time
30   for a manipulator in accordance with an embodiment of the
present invention;

Figures 5a to 5h are a series of graphs depicting an
obstacle avoidance sequence as a function of time, for a

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manipulator in accordance with the present invention;

Figures 6a is a graph depicting the reference link's position relative to the base of a manipulator in accordance with an embodiment of the present invention;

5   Figure 6b is a graph depicting the error value relative to an final position for a manipulator in accordance with an embodiment of the present invention;

Figure 7a is a diagram depicting the movement of a manipulator along a path, and Figures 7b, 7c and 7d are

10   images of a manipulator intersecting a moving target;

Figure 8a is a diagram depicting the use of the methodology in accordance with an embodiment of the present invention when the parts are not physically interdependent, and Figures 8b-8g are graphs depicting a

15   MATLAB simulation of the example depicted in Figure 8a, and Figure 8h is another diagram depicting the use of the methodology depicted in Figure 8a;

Figures 9a-9f are graphs of a MATLAB simulation depicting a multi-manipulator system of a "dog" walking

20   motion, utilising a decentralised control methodology in accordance with an embodiment of the present invention;

Figures 10a-d are graphs of a MATLAB simulation where the decentralised control methodology in accordance with an embodiment of the present invention is utilised to

25   control the orientation of a manipulator link;

Figures 11a-f are graphs of a MATLAB simulation where the decentralised control methodology in accordance with an embodiment of the present invention is utilised to control a bifurcated manipulator module including two arms

30   and a base; and

Figure 12 is a graph of a MATLAB simulation demonstrating the switching between a centralised and a decentralised control methodology.

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DESCRIPTION OF A SPECIFIC EMBODIMENT

General Description

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A control methodology is disclosed which allows a plurality of interdependent units to work co-operatively yet independently to reach a desired outcome. This is achieved through the use of a decentralised control system

10 and methodology, where each of the units establishes and initiates an operation action utilising starting information, that may be derived from any one or more of a desired outcome, and constraining factors. The operation action is usually a desired action that is directed to

15 achieving the desired outcome, but may be a constraint action if constraining factors are present. Once the operation action is defined, the unit initiates that action. This process is iterated with the operation action being updated at each iteration until the desired

20 outcome is reached. The control methodology may find application in a number of disparate fields. However, one natural application is in the control of robots and in particular robotic manipulators.

In the context of the present specification, the

25 desired outcome is generally based on location of a reference portion at a desired fixed position in space. However, it will be understood that the desired position may change over time (i.e. during iteration of the process) by establishing a plurality of intermediate

30 outcomes. In this way, the desired outcome may be the movement along a line or a curve.

In the context of the present specification, the term interdependent refers to constituent parts which are not

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necessarily physically connected, but are constrained by
one another in some form such as being related spatially.
An example of an interdependent system is a robotic arm,
normally termed a "manipulator" in the art.

5   In the example utilising a manipulator, each unit in
the manipulator is generally termed a manipulator module,
a manipulator link or a manipulator portion.

Example Manipulator Module

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        An example of a suitable manipulator module will now
be described, by way of example only. Referring to
Figures 1a and 1b, there is shown a manipulator module 100
in accordance with an embodiment of the present invention.
15 The manipulator module 100 includes a body portion 102
which is capable of housing a joint structure 104 arranged
to allow the module to provide two rotational degrees of
freedom.

        The manipulator module 100 further includes
20 attachment means 106 which are substantially planar
structures in the form of a plate. The plates allow the
module to interconnect to another module (not shown). It
will be understood that in some embodiments, modules may
be integrally moulded with other modules, thereby
25 obviating the need for attachment means.

        The body 102 is also arranged to receive the
actuation means 108. The actuators 108 are connected to
the joint structure 104 to provide relative movement of
the joint structure 104.

30   The actuation means 108 includes a motor 110 which
drives a gear head (not shown). The gear head drives a
belt drive 112 (not shown) which in turn drives a linear
actuator in the form of a ball screw (not shown). The

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linear actuator drives a tension drive, which in the
present embodiment includes a cable. The cable is
connected at one end of the joint 102, and at the other
end to a pulley to allow for bidirectional control of the
5   joint.

        In other words, when the motor is activated, it
drives the gear head, which in turn drives the linear
actuator, causing the cable drive to move, thereby moving
the joint through an angle θ. It will be understood that
10   a similar actuator means is utilised for both arc shaped
portions, thereby providing motorised control for both
degrees of freedom of the joint structure.

        As can be seen, the manipulator module is relatively
compact in size, is completely self contained (i.e. all
15   driving parts are contained within the manipulator
module), and the attachment plates allow the manipulator
module to be easily connected to another module. In
another embodiment, the manipulator may be integrally
formed, such that the joint is integrally formed with
20   either one or both of the elements on each side of the
joint.

        The manipulator module may include communication
means, which may take the form of an electronic interface
(i.e. an electronic bus) that interfaces the motors to a
25   control means. The control means may be a control pad
(such as a joystick) in the case of a manually controlled
manipulator module, or it may be a computing means (such
as a microcontroller or a computer) in the case of a
programmable manipulator module. In other embodiments,
30   the communication means and the microcontroller (or
equivalent) may be wholly contained within each module,
such that each module may operate independently of other
modules.

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The manipulator module may also incorporate appropriate sensors which may be required to sense the surrounding environment, to avoid obstacles or to provide information on some external condition, such as

5   temperature, humidity, etc. In one particular embodiment, the sensor may be an optical encoder, which may be used to measure the proximity of obstacles. Another possible sensor could be a pressure sensor, which may be used to determine whether the manipulator module has come into

10   contact with an external object.

Simple Multiple-Unit Manipulator

Turning to Figures 2a and 2b, there is shown a

15   schematic diagram that depicts an assembled manipulator. The manipulator is comprised of a series of interdependent units, namely links or modules 200a to 200e, each link being connected to a successive link and rotatable about two degrees of freedom, namely an arbitrary "x" and "y"

20   plane. The manipulator is controlled by a decentralised control mechanism, which allows for independent control of each link of the plurality of interdependent units.

The manipulator has a control system that is laid out such that each link of the manipulator has a separate

25   embedded processor which independently controls the motion of the particular link in response to the provision of particular input information, namely the desired outcome (i.e. the position to which the manipulator wants to move) and a reference position (i.e. the position of the

30   reference link, which will be described in more detail later). The input information may also include information regarding the presence of obstacles (which is provided by the proximity sensor).

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It will be understood that whilst this particular embodiment has a separate processor for each link, a central processor could be utilised, in a multi-tasking · mode, to perform necessary calculations on behalf of each

5   link. That is, while one processor performs all calculations, the calculations would be independent and unique for each link.

The manner in which information regarding the reference position is provided to each link may be varied.

10 In the example to be described, each link is provided with information regarding the position of an adjacent link relative to a reference position (i.e. the position of the reference link). However, this is not the only manner in which such information may be passed from link to link.

15 In another embodiment, each link may have a sensor which provides it with information regarding a reference position. In this way, each link may operate independently of other links. However, for convenience, the embodiment described herein relies on information

20 being relayed from one link to the next, as this is a cost effective option when constructing the embodiment.

That is, whilst the physical layout of the embodiment described in Figures 2a and 2b is serial in nature, and therefore information distribution occurs in a serial

25 manner, the underlying control methodology of each link is independent of the other links. The control may be achieved (i.e. information may flow from link to link) in a tree, net or parallel structure.

In Figure 2a, the information input to each link is

30 not manipulated and the information output from each link may be manipulated before it is passed to a successive link. However, it will be understood, that in other embodiments, such as the one disclosed in Figure 2b, the

information input to each link and the information output
from each link may be manipulated in any appropriate
manner. Such information manipulation may be advantageous
as the partial transformation of information may

5   preferably minimise the transfer of information from link
to link. Moreover, as a corollary, by minimising the
amount of information transferred between each link, the
amount of data received by each link is also
correspondingly decreased. This may reduce the need for a

10   wide data bus between links and allow for faster response
times.

In the present embodiment, the links are arranged in
a serial structure, as the manipulator as described is
particularly suitable for the collection of objects which

15   are arranged in a random fashion (e.g. fruit located on a
tree or vine). It will be understood that the methodology
described herein is not restricted to serial structures,
and may be utilised to control any structure of
interdependent units.

20   The manipulator of the embodiment operates in the
following manner.

A desired outcome (i.e. a desired position) is
recognised by the reference link of the manipulator. The
desired position may be determined by any appropriate

25   means, such as a stereo vision module or similar device,
or it may be provided by an operator or pre-programmed
into the manipulator. Once the desired position, dubbed

$"\overline{X}_d$ is determined, each link is provided with the desired
position and programmed such that each link's prime

30   objective is to position a reference portion (in one
embodiment the end link of the manipulator) at the desired
position.

Each module "i" is provided with two local input

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(information) values, $^{i+1}\overline{X}_a$, $^{i+1}\overline{X}_d$ which represent the actual position of the adjacent link (i+1) and the desired position of the adjacent link (i+1). These are, in effect, transformed values of the original reference

5   position and the desired position. However, it will be understood that each link could utilise the original values and apply appropriate transformations to derive a and desired action for each link in its own frame of reference.

10   Using the input information provided and equations 1 and 2 (below), the desired action for each link can be determined, and therefore the rotational errors in the link may also be determined in the particular link's frame of reference.

15
$$^{i}\overline{x_a} = \overline{f_2}\left(^{i}\overline{x_a}, \theta_{x_{i+1}}, \theta_{y_{i+1}}, l_i\right) \quad (1)$$

$$^{i}\overline{x_d} = \overline{f_3}\left(^{i}\overline{x_d}, \theta_{x_{i+1}}, \theta_{y_{i+1}}, l_i\right) \quad (2)$$

Once the desired position for each link is

20   determined, in its own frame of reference, the rotational error of each link may then be computed using equations 3 and 4 (below).

$$^{i}\overline{x_{err}} = \overline{f_4}\left(^{i}\overline{x_a}, ^{i}\overline{x_d}\right) \quad (3)$$

25

$$\left[\theta_{x_i}, \theta_{y_i}\right]^{T}_{err} = \overline{f_5}\left(^{i}\overline{x_{err}}\right) \quad (4)$$

Where f_j refers to a specific function appropriate to the link structure and the link interconnectivity.

30   Once the desired action for each link is calculated, an operation action is established for each link. That

is, the desired action is transformed into a command to move the link in an appropriate manner. Each actuator in each link may then be operated to move the link under this operation action. This process is iterated with the input

5   information and operation actions updated. The process continues until the calculated rotational errors are reduced to zero, thereby indicating that the desired outcome has been reached.

Therefore, the manipulator operates by allowing each

10   link in the manipulator to perform a desired local action, by providing each link with information pertaining to the desired outcome and a reference position, to allow each individual link to transform the information into a desired action that is compatible with and contributes

15   towards the desired outcome. This advantageously allows each link to make local decisions independently of other links, whilst still contributing to the desired outcome. This is particularly useful where one or more of the individual links is presented with an obstacle or a series

20   of unforseen obstacles, or if one link in the plurality of links ceases to operate. Both the presence of an obstacle and the cessation of operation of a link may be modelled as a constraint factor (i.e. an action which restricts the movement of at least one module). Once the presence of a

25   constraint factor becomes known (for example, through the use of a sensor), the constraint factor can be taken into consideration, and a constraint action can be established both locally and universally. Alternatively, if one unit ceases to operate, this may be ignored by other units with

30   the system not establishing a constraint factor for the failure of that unit. The other units may continue to operate as they each establish their operation action independently of the other units.

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That is, when an individual link detects or becomes
aware of an obstacle, the link may adjust its own path and
movement to avoid the obstacle, whilst simultaneously
balancing the constraint action (i.e. avoiding the
5   obstacle), with the primary objective of moving the
manipulator to its end position. Alternatively, depending
on the type of constraint, the constraint action may be
performed instead of the desired action. That is the
desired action does not automatically translate into an
10   operation action where constraint factors are present, the
operation within may be the constraint action or it may be
some combination or average of the desired action and the
constraint action.

        In a particular embodiment, each link may also be
15   capable of sending a broadcast message to other links,
such that they may become aware of obstacles in advance,
and also assist in taking corrective action to avoid the
obstacle. In other words, constraint factors relating to
one unit may be utilised in establishing a constraint
20   action for other units. This will further the collision
avoidance capabilities of the manipulator.

        Furthermore, if one link breaks down or becomes
inoperative, successive links can adjust their constraint
actions accordingly to compensate for the problematic
25   link. In other words, the decentralised control method
provides redundant manipulator control, so a fault in one
or more links does not necessarily render the manipulator
inactive. As a corollary, extra links may also be added
to the manipulator without the need to reprogram the
30   manipulator.

        That is, at least an embodiment of the present
invention allows for dynamically reconfigurable
manipulators. This may be particularly useful in

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situations where the length of the manipulator may need to
be altered at short notice (e.g. in fruit picking
applications, extra links may be added to the manipulator
to compensate for environmental factors such as tree
5   growth, thicker foliage, etc.).

        Advantageously, the manipulator can dynamically plan
a path, which is important in applications where tasks are
not repetitive.

        An example of a system in accordance with an
10 embodiment of the present invention will now be described,
with reference to Figures 3 and 4.

        A simulation, utilising the MATLAB Simulink software
application, was produced to demonstrate the practicality
of the manipulator control mechanism described herein. In
15 the simulation, each link is aware of its own angular
offsets, morphology and the distance from the reference
position to the desired outcome position.

        The links are physically connected in series, though
they function independently of each other and work in
20 parallel to achieve the desired outcome. The simulation
layout is arranged for information flow in one direction
from a defined reference link through to the base link in
the manipulator.

        The link properties include two degrees of freedom
25 per link, which allows each link to move on the surface of
a sphere. Communication between successive links and
embedded processors on individual links takes place in the
same manner as the manipulator shown in Figures 2a and 2b.

        The manipulator utilised in the simulation is
30 comprised of six 100 unit long links ("unit" being any
arbitrary measure of length). In the simulation, a
desired outcome (i.e. the desired final position of the
reference portion link) is kept constant relative to the

base position.

Two examples where the manipulator's structure is
altered and then controlled to achieve a desired outcome
position will now be described. It is to be noted that
5   after reconfiguration of links, no re-programming of the
system is required.

Figure 3a shows the normal successful motion of a
regular manipulator instructed to move from the initial
condition (-600,0,0) to the final position, set at
10   (300,300,350).

The first simulation demonstrates the dynamic
abilities of the manipulator when a link is modified. The
third link from the base, which was originally 100 units
long, is replaced with a link of a different length, now
15   300 units long. By keeping all other parameters constant
and without informing other links of the change, the
manipulator is instructed to reach the goal end position
(300,300,350). Figure 3b shows the resulting motion
profile of the manipulator. As can be seen in the figure,
20   the manipulator is able to successfully reach the same
final position.

The second simulation simulates the failure of one
link during motion. The manipulator attempts to reach a
given final position, but at some point during the
25   simulator, one link's capability is lost. Figure 3c shows
the ability of the manipulator to circumvent the fault
when moving towards a final position. In the example, the
link closest to the reference link was caused to fail some
time into the goal-seeking routine. Figure 3c shows the
30   resulting motion profile of the manipulator in again
successfully reaching the set goal position.

In the plots shown in Figures 3a to 3c, no
optimisation of the manipulator's motion profiles have

been used through the use of varying time constants in
each links.

Another advantage of using a redundant manipulator in
reaching an final position is the ability of the
5   manipulator to avoid obstacles. Referring to Figure 4,
there is shown a six link 12 degree of freedom manipulator
approaching a final position (150,0,500) while avoiding
two obstacles. The initial condition of the manipulator
places the reference link at (-450,0,386) as shown in
10   Figure 4a. The obstacles used are two bars with
coordinates (-200,-300≤y≤300,300) and (0,-300≤y≤300,150).

To avoid obstacles, each link's proximity sensor is
activated when an obstacle encroaches into a hypothetical
cylindrical shell of radius 50 units centred on the axis
15   of each link. The link may provide an actuator motion (a
constraint action) so as to repel itself from the obstacle
in the shortest possible path (i.e. by moving away from
the obstacle). The function used for obstacle avoidance
in the simulation is
20   where q = 1 when the proximity sensor is idle and q = 0
when the proximity sensor is activated.

$$\left[\theta_{x_i}, \theta_{y_i}\right]^T_{errnew} = 2 \bullet (q - 0.5) \bullet \left[\theta_{x_i}, \theta_{y_i}\right]^T_{err} \qquad (5)$$

25   In the simulation, heuristic optimisation of the
manipulator's motion is achieved by modifying the time
constants of the first order response of each link
(i.e. the speed of response). The shortest time constant
(or the "fastest" speed of response) is given to the link
30   nearest to the reference link, incrementally increasing by
a factor of 2 for each successive link.

Figure 3 shows the reconfigurable capabilities of the
decentralised control approach where the manipulator

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design can be altered through the introduction of links
with irregular properties depending on application
requirements. The links contain self-reliant data, acting
as plug-and-play components in the manipulator. The
5   redundant nature of the manipulator further allows for
fault tolerance as shown in Figure 3c. If link failure
occurs, the remaining links individually accommodate
changes, dynamically providing a means for reaching the
goal. The manipulator's paths intuitively appear close to
10 optimal for each scenario, dynamically adjusting to
accommodate for system changes.

        Figure 4 shows the motion profile of the manipulator
successfully negotiating the two obstacles and reaching
the set goal. As can be seen in Figure 4a, the
15 manipulator is initially presented with an obstacle, and
as can be seen in Figures 4b through 4g, each link in the
manipulator adjusts its position relative to the two
obstacles to successfully negotiate the obstacles, until
the final desired position is reached (Figure 4h).

20   The obstacle avoidance scenario in Figure 4 shows how
the manipulator negotiates obstacles, successfully
reaching the final position. It is noted that the
decentralised control algorithm allows for the reference
link to temporarily move away from the final position when
25 negotiating obstacles.

        The serial layout of the manipulator further provides
a means of determining motion around obstacles. Where the
obstacle is near the base of the manipulator, the links
attempt to reach the final position by orientating around
30 the obstacle. However if the obstacle is a significant
distance from the base of the manipulator, the links will
drive the manipulator past the obstacle, retracting the
reference link rather than wrapping around the obstacle.

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Experimentation with the manipulator time constant revealed that it was advantageous for the links nearest to the reference link to be more responsive then those further away from the reference link. This enabled the
5   reference link to be in transit to the final position before links away from the reference link had the opportunity to take affect, in order to favour line of sight movement of the reference link relative to the final position.

10   The independent motion of each link can be seen in Figure 5 with desired motions being hindered where links avoid an obstacle. The sequential avoidance of the obstacle at (-200,-300≤y≤300,300) by links 4, 5 and 6 are manifested by non-monotonic actuator velocities in
15   respective motion profiles. These procedures are coupled, e.g. link 4 and link 5 avoid the obstacle simultaneously.

Similarly, avoidance of the obstacle at (0,-300≤y≤300,150) by links 2 and 3 also involves non-monotonic actuator velocities.

20   Figure 6 shows the position of the reference link relative to the base and relative to the final position. Though some individual actuator motion characteristics are evident, the elicitation of the required individual link motions is not evident. The reference link error in
25   Figure 6b, which is used to drive the links, shows distinct non-monotonic behaviour, which normally only occurs with complex centrally controlled systems. This is achieved simply by decentralising the motion control.

The changes in motor directions as observed in
30   Figure 5 might appear at first undesirable e.g. link 6 angles return close to their original values. When viewing the overall motion in Figure 4 such behaviour is desirable in finding a smooth path around the obstacles to

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the final position.

Therefore, at least an embodiment of the present
invention provides a system and method for controlling a
reconfigurable redundant manipulator.

5   The system and method readily accommodate for system
reconfigurability, dynamically adjusting motion and
utilising the flexibility of the complete manipulator.
The capabilities of the decentralised control method
include, redundant control, reconfigurable modular

10   designs, fault tolerant motion control, dynamic path
planning, and real-time obstacle avoidance capabilities.

It will be understood that whilst the embodiment
described herein makes reference to a manipulator and the
movement of the manipulator to a defined point in space,

15   the decentralised control methodology may be applied to
any system which incorporates a plurality of
interdependent units.

Motion along a Defined Path, and/or Intersection with a

20   Moving Object

For example, the desired outcome need not be limited
to a movement towards a fixed point in space. The point
in space can change over time, allowing for motion along a

25   defined path or for the manipulator to intersect the path
of a moving target. In other words, the outcome may have
a time dependence component.

The control methodology remains unchanged as
calculations within each module can be iterative, so at

30   each iteration, the desired outcome can be modified so
that the manipulator is constantly moving towards the
desired outcome. This effectively creates a movement akin
to the arm moving along a defined path or tracking a

moving object. An example of the motion described above
is given in Figures 7a-7d. As can be seen, particularly
in Figure 7a, the manipulator can be programmed to move
along a defined path by merely changing the desired

5 outcome as the arm approaches the desired outcome. In
Figure 7a, the manipulator follows a path defined by the
equation (x,y) = (-300 + mt, 400) for mt in the set
(0,600).

In more detail, the desired outcome as observed by

10 the individual i^{th} module is a point $^{i}\overline{x}_{g}$. This point need not
be limited to a fixed point in space. The point can be
time dependant, allowing for the critical point $^{b}\overline{x}_{e}$ to
follow a trajectory of a time dependant desired outcome.
This can be achieved by redefining the desired outcome, as

15 observed by the end module $^{n}\overline{x}_{g}$, prior to passing this
information through to the subsequent modules. This is
outlined in equation (6) below.

$$^{n}\overline{x}_{g}(t) = f_{goal}\left(^{n}\overline{x}_{g}(t-1), t\right) \qquad (6)$$

20

The control methodology remains unchanged as
calculations within each module utilizing the outcome are
iterative. An additional capability which may be
incorporated into the time dependant motion of the

25 manipulator is the approximate motion of the manipulator
through various waypoints. This introduces an additional
parameter by which the desired outcome as observed by the
end module $^{n}\overline{x}_{g}$ is defined (see equation 7).

30 $$^{n}\overline{x}_{g}(t) = f_{goal}\left(^{n}\overline{x}_{g}(t-1), t, r_{1}(t-1)\right) \qquad (7)$$

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The additional parameter r_1 introduces the capability of the manipulator to vary the outcome when for example the outcome is within a given range from the critical point as defined by equation 8.

5

$$r_1(t-1) = \sqrt{{}^n x(t-1)_g^2 + {}^n y(t-1)_g^2 + {}^n z(t-1)_g^2} \qquad (8)$$

In the below example the critical point ${}^b\overline{x}_g$ follows a trajectory of a time dependant goal defined by equation 9

10   for $t \in 0,100$; ${}^n x_g(0) = -300$; ${}^n y_g(0) = 400$

$$\begin{aligned} {}^n x_g(t) &= {}^n x_g(t-1) + 6t \qquad (9) \\ {}^n y_g(t) &= {}^n y_g(t-1) \end{aligned}$$

15   A further capability which may be incorporated into the motion of the manipulator is through intersecting the path of a moving object. This redefines the parameter r_1 by which the desired outcome, as observed by the end module ${}^n\overline{x}_g$, is defined (see equation 10).

20

$$^n\overline{x}_g(t) = f_{goal}\left({}^n\overline{x}_g(t-1),t,q\right) \cdot r_2(t-1) \qquad (10)$$

The parameter r_2 introduces the capability of the manipulator to enable the outcome when for example the

25   outcome is within a given range q from the critical point as defined by equation 11.

$$r_2(t-1) = \left\{ \begin{array}{l} \sqrt{{}^n x(t-1)_g^2 + {}^n y(t-1)_g^2 + {}^n z(t-1)_g^2} \le q = 1 \\ \sqrt{{}^n x(t-1)_g^2 + {}^n y(t-1)_g^2 + {}^n z(t-1)_g^2} > q = 0 \end{array} \right\} \qquad (11)$$

In the below example the manipulator is demonstrated catching a ball where the ball is the desired outcome, for the range $q = 200$.

5   Centring a Platform Based on the Centre of Mass (Stewart Platform)

Moreover, the relationship between the units need not be limited to the physical connection between modules in a

10   manipulator. At Figure 8a, there is shown a diagram depicting a situation where two robotic manipulators interact to place the centre of mass of a non-rigid object at given point in space. Each robotic manipulator may be considered to be a subsystem of the system (i.e. the

15   Stewart platform). The control methodology remains unchanged though the desired outcome is now characterized by the object's centre of mass, where the camera now observes the object's centre of mass position and goal position, passing it as previously from module to module.

20   A simulation of the permutations of such a device is shown in Figures 8b-g.

The critical point for the interacting two link manipulators in the above example is the centre of the beam, which is:

25

$$\left(\theta_a, \bar{X}_a \right) \qquad (12)$$

This point is orientated by each of the manipulators such that the critical point moves towards the desired

30   point and orientation:

$$\left(\theta_d, \bar{x}_d \right) \qquad (13)$$

as shown in Figure 8h. Each subsystem (i.e. each
manipulator arm) continues to have a desired outcome,
5   namely the centring of the mass, but each manipulator arm
now has an intermediate outcome, in that each manipulator
arm is acting independently of the other manipulator arm.

Complex Multi-Limb Systems

10

        Of course, the methodology could also be expanded to
more complex motion, such as the mimicking of the walking
of a dog. The diagonally alternate leg pairs are used to
maintain the orientation of the body while propelling it
15   forward in a manner similar to all previous examples.
        Simultaneously, the other diagonally alternate leg
pair use their respective body connections as bases to
lift the feet (shortest link length) and move them
forward. These motions are then switched repeatedly
20   resulting in a walking motion, as shown in Figures 9a-f.
        In the dog walking example, the control methodology
is utilised to control the motion of each leg relative to
each other leg, and also each section of a leg in relation
to other sections of the leg. That is, the "units" may be
25   defined as one leg in relation to another leg, and
separately, each link in a leg in relation to the other
links. Therefore, the control methodology is being
utilised in two different ways, to perform two different
tasks. Both tasks occur simultaneously and do not
30   interfere with each other. In other words, once again,
the desired outcome is for the dog to walk. This is
broken down into a number of intermediate outcomes, namely

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the motion of each leg relative to each other leg. By
utilising a series of "nested" outcomes, one for each
structure (namely the movement of each link in a leg, and
the movement of each leg as a whole relative to each other
5   leg) very complex desired outcomes can be achieved.

Bifurcated (And Other Multiple-Arm) Systems

Another example of a complex structure where the
10   methodology may be applied is a bifurcated (or n-tuple)
manipulator with a common base.

In the example shown in Figures 11a-f, there is
provided three connected manipulators each composed of
three links and assembled into a Y formation. The
15   bifurcated manipulator may be seen as the "system", with
each of the three manipulators forming a subsystem.

The desired outcome may be to place each of the two
manipulator arms in a desired position. This can be
broken down into the two end effecters having different
20   intermediate outcomes. In the example, the left end
effecter wishes to move to the point (-400,200) and the
right end effecter wishes to move to the point (100,300).

The individual upper sections use the unchanged
control methodology to reach for their respective goals,
25   $^{n}\bar{x}_{g1}$ and $^{m}\bar{x}_{g2}$.

The base section, comprising three links, also has an
intermediate outcome sympathetic with the desired outcome
of moving each of the two end effectors to their
respective locations. The base section uses combined
30   information sourced from both of the top sections in
determining the 3rd link's intermediate outcome. In other
words, by taking an "average" of the intermediate outcome
for each individual manipulator arm, the base section

devises its own intermediate outcome which allows both
manipulator arms to reach their intermediate outcome, and
in turn, achieves the desired outcome for the system as a
whole (assuming there is sufficient length as shown in
5   equations 14 and 15).

$$^i\overline{x}_g = \frac{^{i+1}\overline{x}_{g1} + ^{i+1}\overline{x}_{g2}}{2} \quad (14)$$

$$^i\overline{x}_e = \frac{^{i+1}\overline{x}_{e1} + ^{i+1}\overline{x}_{e2}}{2} \quad (15)$$

10

The first and second links in the base section
receive $^{i+1}\overline{x}_g$ and $^{i+1}\overline{x}_e$ from their respective modules as
required using the control methodology described for the
simple manipulator example. As shown in Figure 11a-f, the
15   Y formation successfully reaches the intermediate outcome
for each manipulator arm, thereby achieving the desired
outcome. The base section orientates itself so as to aid
the speed of motion in reaching the desired outcome.

20   Other Types of Motion

It will also be understood that the same methodology
may be applied to other types of motion, such as
rotational motion. The simulation depicted in
25   Figures 12a-d demonstrate orientation control of the end
effecter (i.e. where the end effector can rotate). This
is achieved by assigning the task of orientation control
to the end link of the manipulator, using equation 16 for
a planar manipulator:

30

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$$\sum_{i=1}^{n} \theta_i = \theta_d \qquad (16)$$

where,

$$\dot{\theta}_n = f\left(\sum_{i=1}^{n} \theta_i, \theta_d\right) \qquad (17)$$

Whilst embodiments of the present invention refer to the use of a decentralised control methodology, it will be understood that the decentralised control methodology may be utilised in conjunction with traditional centralised control methodologies. In some situations it may not be appropriate to utilise only a decentralised control methodology. For example, in the case where a manipulator is utilised for global systemic mapping of an environment while searching for a goal, a mixed strategy is useful.

That is, the use of a centralised control methodology is more appropriate while the manipulator is mapping (i.e. scanning in a systematic manner across an area with defined boundaries). However, once the manipulator receives information regarding a desired outcome (i.e. it detects a target and is instructed to move towards the target), decentralised control is more appropriate.

The mixture of decentralised and centralised control is shown in Figure 12, which depicts a simulation where the manipulator links are initially locked to provide only two degrees of freedom (thereby making the system non-redundant), and also allowing the system to easily perform simple movements in a defined area. Once a more specific desired outcome is required, the manipulator is switched to decentralised control, unlocking the links and introducing redundancy (six degrees of freedom), thereby

increasing flexibility.

In one embodiment, information concerning each links angle is passed to a CPU. To control the two degrees of freedom system centrally the two fixed links are given by
5   equations 18 and 19:

$$l_1 = \sqrt{{}^1x_4^2 + {}^1y_4^2} \qquad (18)$$

where ${}^1\overline{x}_4$ is the base of the 4th link in the base of 1st
10   link's frame of reference; and

$$l_2 = \sqrt{{}^4x_e^2 + {}^4y_e^2} \qquad (19)$$

where ${}^4\overline{x}_e$ is the position of the end effecter in the base
15   of 4th link's frame of reference.

The variables $\theta_2, \theta_3, \theta_5, \theta_6$ are fixed for the centralized control mode. With the 2 variables θ_1, θ_4 controlled by equation 20:

20

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_4 \\ 1 \end{bmatrix} = \underline{J}^{-1} \cdot \begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ 1 \end{bmatrix} \qquad (20)$$

In example given, the initial motion is centralized with only two degrees of freedom, making the manipulator a non-redundant system. During the motion there may be a
25   requirement to free the actuators, thereby introducing redundancy (six degrees of freedom) and flexibility into the manipulator's motion.

When redundancy is introduced, a decentralised control methodology in accordance with the embodiment is

more appropriate, since it ameliorates the issues
associated with redundant systems.

It will be understood that the manipulators and
robots described are not constrained to any particular
5   scale. The methodology is equally applicable to large
industrial manipulators and robots, as to small robots for
specialised applications. For example, the methodology
could be utilised in a robot which picks fruit, or a robot
which locates and removes debris from a field or a factory
10   floor. Equally, the methodology could be applied to an
intelligent surgical instrument which could self-propel
through the body of a patient to a predetermined location.

The methodology is particularly suitable for delicate
work, as it has many qualities which make it suitable for
15   such work.

These include the ability to navigate unfamiliar
paths, the ability to avoid obstacles, the ability to
continue to operate even if a portion of the manipulator
breaks down, and the ability for the manipulator to be
20   reconfigured for different applications without needing to
make any modifications to the methodology.

Modifications and variations as would be apparent to
a skilled addressee are deemed to be within the scope of
the present invention.